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A CRITICAL EVALUATION OF THE COGNITIVE PENETRABILITY OF POSTURE

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Background/Study Context*: Interactions between postural control and cognitive activity as evidenced by dual-tasking studies are common, and especially pronounced in the elderly. Some authors have used this finding to suggest that posture is "cognitively penetrable."*

Methods*: The authors present a critical look at the "cognitive penetrability of posture" concept. The authors first trace the notion back to Pylyshyn (1980,* Behavioral and Brain Sciences, 3, *111–169) in the context of visual information processing.*

Results*: The authors then argue that dual-tasking interference effects do not prove that posture is penetrable by cognition.*

Conclusion*: The authors conclude that it may be valid to study cognitive penetrability of posture, but that such an endeavor is served best by adopting a hierarchical model of action control.*

The increased risk of falling in the elderly has led numerous researchers to investigate how cognitive factors such as attention relate to postural stability. Pertinent literature has consistently demonstrated that (a) elderly need more attention to regulate their balance compared with young adults, and (b) elderly find it more difficult to combine a balance task with a cognitive task (e.g., Woollacott & Shumway-Cook, 2002). Elucidating the relationship between cognition

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and balance has clear clinical implications, and may lead to the incorporation of attention training in rehabilitation schemes to enhance postural stability (for a recent example, see Li et al., 2010).

The contribution of attention to the regulation of balance is typically studied using the dual-task paradigm, which combines postural and cognitive tasks, ideally (but not consistently) with different levels of difficulty. The literature on posture-cognition interactions is vast, and some excellent reviews and empirical studies, some geared especially toward aging, have been published (e.g., Brauer, Woollacott, & Shumway-Cook, 2002; Frazier & Mitra, 2008; Huang & Mercer, 2001; Huxhold, Li, Schmiedek, & Lindenberger, 2006). Interaction effects of posture and cognition are usually interpreted as a reflection of the attentional demands involved in the joint execution of the two tasks (e.g., Redfern, Jennings, Mendelson, & Nebes, 2009). In this context, "cognitive penetrability" is an often-used term, which has been introduced to indicate the extent to which cognitive processes (attention, memory, etc.) impact on the regulation of the postural control system.

Our current aim is to clarify the relation between dual-task findings, and to evaluate the merits of the notion of "cognitive penetrability." To anticipate, we aim to demonstrate that the dual-tasking paradigm can help to elucidate the supposed competition for attentional resources between postural control and cognition, but that such findings are not informative about the cognitive penetrability of posture, as this is a different topic altogether. To this end, we present a brief treatment of the history and scope of the cognitive penetrability concept, and the way it has been used in the motor control literature.

The phrase "cognitive penetrability of postural responses" was probably first coined by Stelmach and Worringham (1985), but the notion gained significant popularity since the study of Teasdale, Bard, LaRue, and Fleury (1993). The phrase has surfaced since then in several papers investigating the influence of cognition on the regulation of posture (e.g., Caudron, Boy, Forestier, & Guerraz, 2008; Frazier & Mitra, 2008; Mitra, 2003, 2004; VanderVelde, Woollacott, & Shumway-Cook, 2005), the majority of which make use of a dual-tasking paradigm. Teasdale et al. (1993) studied how balance requirements interacted with cognitive performance in different age groups. Subjects (healthy young and elderly) were asked to stand stably and quietly on a forceplate. At unpredictable moments a tone was presented, upon which subjects had to press a handheld button as soon as possible. Importantly, the erratic center-of-pressure (COP) displacements during standing were monitored online and the stimulus was presented randomly when the COP was either in a central or a more eccentric position. For the elderly subjects it was found that when the auditory stimulus was presented if the COP happened to be in an eccentric position (i.e., where body posture was somewhat unstable), the reaction times (RTs) were elevated significantly compared with a more central position. Such an effect was not evident for the young subjects. This finding was taken to suggest that the elderly subjects required more "central cognitive processes" for the regulation of posture, and that there was likely an "interdependence between the sensorimotor and the cognitive systems in the control of posture" (p. 11). Numerous subsequent studies have reached similar conclusions and offered similar interpretations.

The study by Teasdale et al. (1993) can be considered a landmark paper that sparked off a whole gamut of posture-cognition interaction studies. We have no intention to criticize this influential study, but we believe the phrase "cognitive penetrability of posture" as used in the literature raises more questions than it answers. Firstly, with respect to the original study: the term "cognitive penetrability" was only used in the title of the Teasdale et al. (1993) article, whereas in the actual text itself the term "interdependence" was used to refer to the interaction between central cognitive processes and peripheral sensorimotor processes. In the present paper, we argue that "interdependence" is in fact a much more suitable term than "cognitive penetrability." Second, Teasdale et al. (1993) found that an eccentric position of the center of pressure (COP) required more attention than a stable (center) position, as evidenced by hampered information processing. In this regard, it would arguably have made more sense to talk of "postural penetrability of cognition" instead of "cognitive penetrability of posture control," that is, if one wishes to use the term in the first place.

COGNITIVE PENETRABILITY: BACKGROUND

Pylyshyn (1980, 1999) was one of the first to coin the phrase "cognitive penetrability" in the field of cognitive science, a notion germane to Jerry Fodor's modularity of mind hypothesis (1983). Pylyshyn was interested in whether central cognitive processes (beliefs, expectations, etc.) could influence visual information processing. He argued that vision, especially during early stages of information processing, operates according to its own set of rules and cannot be influenced by cognition. According to this view, the visual apparatus processes a set of sensory "propositions" (retinal input), leading to a perceptual "conclusion" (i.e., a visual experience). Importantly, this process of sensory "reasoning" is assumed to be unaffected by other mental faculties. An often-cited example concerns our experience of visual illusions such as the moon illusion. Despite our firm knowledge that the moon does not change in shape and size, we cannot help but judge the moon to be larger when it is close to the horizon than when it is high up in the skies. This is a strong argument in favor of the thesis that vision is impenetrable to cognition. Note that this thesis does not rule out the possibility that vision is penetrable by other modules. For example, it has been shown that visual perception and auditory perception can interact in unexpected ways, as illustrated for example by the McGurk effect (McGurk & MacDonald, 1976). Another example of cognitive impenetrability is found in the realm of affect; it has been argued that emotions and moods (e.g., depression) are resistant to cognitive efforts to change the contents of our affective experience (e.g., Gerrans & Kennett, 2006). Emotions and moods seem to have their own logic, in that they all have a common script or structure (e.g., Scharland, 2006) that cannot be rewritten or overwritten by cognition. The logic thus dictates that emotions also qualify as cognitively impenetrable faculties. On the other hand, a study by Dunn, Dalgleish, and Lawrence (2006) showed that the reward/punishment schedule of the Iowa Gambling Task (a test designed to measure emotional decision making) was cognitively penetrable. This was taken to mean that decision making is influenced by the anticipated consequences of behavior, both on a conscious and a nonconscious level, consistent with Damasio's (1994) influential somatic marker hypothesis.

It is important to realize that cognitive impenetrability does not imply complete independence. In the case of vision, there are numerous instances in which beliefs, expectations, knowledge, etc., codetermine the contents of our visual experience. For example, we may deliberately choose to squint or focus our eyes, to close our eye, push on our eyeball with a finger, etc. In a similar vein, we can make a conscious decision to focus our attention on certain parts of a visual scene for the purpose of visual inspection or disambiguation. By way of another example, if we are engaged in a difficult cognitive activity (say, mental arithmetic), we may temporarily shut our senses from external input. In all these instances visual experience is clearly affected by our will. As a final example, our knowledge base allows us to perform sophisticated perceptual recognition and classification, such that, for instance, an art expert "sees" other things in a painting than a nonexpert. These examples imply that the contents of our visual experience are partly determined by cognition. But as argued by Pylyshyn, such examples of interaction between vision and cognition in no way invalidate the central thesis that vision is impenetrable by cognition. What cognition does, instead, is setting the stage in a top-down fashion in which the visual system can operate, albeit according to its own logic.

COGNITIVE PENETRABILITY OF POSTURE

Although the notion of cognitive penetrability has been mainly applied to visual awareness, a number of studies have applied this notion to the organization of movement (e.g., Paillard, 1991), especially the regulation of posture, but recently also to motor sequencing (e.g., Fraser, Li, & Penhune, 2010). We believe two important caveats are in place when we try to study the "cognitive penetrability of posture control" (and, by extension, other motor activities). First, it is questionable whether the dual-tasking paradigm is appropriate to study cognitive penetrability in the first place. The cognitive penetrability thesis as formulated by Pylyshyn (1980, 1999) refers to the putative influence of the contents of one module (e.g., cognition) on another module (in the present case, posture). But the posture-cognition dual-tasking paradigm is usually applied to answer a related, yet different, question: The aim of dual-tasking is to highlight the conditions under which cognition and posture make use of a hypothesized common pool of attentional resources that can be deployed to facilitate performance on either task. An often-voiced conjecture is that humans possess a limited set of central attentional resources that are strategically allocated to various cognitive and motor tasks, such as the regulation of balance (e.g., Huang & Mercer, 2001; Woollacott & Shumway-Cook, 2002). The logic behind the dual-task paradigm stipulates that as one task becomes more difficult (and thus requires more resources), performance of other tasks deteriorates, but only if the tasks make use of the same resource pool. Dual-tasking studies are concerned predominantly with the allocation of processing resources among two or more tasks that are performed simultaneously, such as working memory and selective attention (e.g., Stins, Vosse, Boomsma, & de Geus, 2004).

With respect to posture-cognition dual-tasking effects (and changes therein, for example with aging), these effects are attributed in like fashion to a strategic allocation of processing resources to the various subtasks, using some sort of prioritization principle (e.g., Doumas, Smolders, & Krampe, 2008) and/or a mechanism of divided attention (Huang & Mercer, 2001). Note that, with a few exceptions (Li, Lindenberger, Freund, & Baltes, 2001), the majority of studies have failed to control how subjects allocate attentional resources to the various tasks (e.g., balance and cognition). Crucially, interference between tasks does not mean that the *contents* of one task dictate the *contents* of the other task; interference means that the combined mental "fuel" required by both tasks has reached its limit, so that one task (or both) can no longer be performed in an optimal fashion. Thus, the dual-task paradigm is mainly concerned with quantifying the attentional demands of concurrent task performance, and less so with the question whether information processing on one task, such as cognition, has a direct impact on parameters of the "motor program" (see below).

Interpretation of posture-cognition dual-tasking results is complicated further by the fact that postural changes during dual-tasking do not necessarily reflect postural *decrements*. Empirically, the field of posture-cognition dual-tasking is riddled by conflicting, often diametrically opposed results. Redfern et al. (2009) pointed out that experiments using a cognitive task (working memory) and a concurrent postural task in older adults have yielded conflicting results. In a similar vein, Fraizer and Mitra (2008) and Prado, Stoffregen, and Duarte (2007) reported that studies using healthy adults have found postural deterioration with a cognitive secondary task, whereas other studies found no effect at all, and still others even found postural improvements. Part of the discrepancy may be due to the fact that it is not always clear what qualifies as postural deterioration. Particularly in the field of postural disturbances due to aging or pathology, it is common to equate high variability of body sway with low postural stability (hence, poor postural performance). However, several authors have questioned this assumption, and argued that body sway can be strategically modulated to facilitate performance of the secondary ("suprapostural") task (e.g., Stoffregen, Hove, Bardy, Riley, & Bonnett, 2007; Stoffregen, Smart, Bardy, & Pagulayan, 1999)—at least with respect to situations involving postural stabilization and visual fixation. In a similar vein, Fraizer and Mitra (2008) argued that postural control not only guarantees successful balance, but also provides a physical substrate for perceptual-cognitive tasks. We believe there may be other reasons besides reduced postural stability that may explain the often-observed increase in body sway in dual-tasking, but, as far as we know, have never been tested. One possibility is that the increase in body sway during cognitive activity reflects unintentional attempts of the actor to increase arousal by self-generated bodily motions, thereby facilitating information processing. Another possibility is that the cognitive activity is mirrored in subtle body movements that facilitate information processing, but are not typically recorded (e.g., silent vocalization, head nodding, or hand motions during problem solving). For example, Carlson, Avraamides, Cary, and Strasberg (2007) found that hand gestures performed during mental arithmetic tasks can serve as a form of external working memory, thereby supporting the representational and computational activities needed to accomplish the tasks (see also Schwartz & Black, 1996). Thus, increased bodily motions might have a causal role in cognitive activity, and the resulting increased body sway might then be misinterpreted as balance loss. This issue clearly requires further testing, but in our view underscores the thesis that the control of posture and the control of cognitive activity mutually influence each other, and are thus "interdependent."

A second problem pertaining to the cognitive penetrability of posture control is that the mere observation that motor activity (as in postural adjustments) interacts with cognitive activity does not necessarily mean that the organization of the movement pattern is subject to conscious awareness and control. This point was already made by Pylyshyn (1980, 1999) in the context of visual awareness, but it also applies to the issue of the cognitive penetrability of action. One way of looking at maintaining upright stance is that it represents an ongoing perceptuomotor activity, against the background of which we can perform desired actions (cognitive, manual, or otherwise). It is open to debate whether observed changes in this background activity are attentional in nature, or that they reflect autonomic postural adjustments to changes in task requirements. To give an example, most of us would probably agree that the control of respiration is an autonomous process that abides by homeostatic principles governing bodily processes. However, respiration is clearly affected by psychological factors. For example, respirational parameters have been found to be affected by the emotional state of the actor (e.g., Gomez, Zimmermann, Guttormsen-Schär, & Danuser, 2005; Homma & Masaoka, 2008), by mental work load (e.g., Kotses, Westlund, & Creer, 1987), and by imagined physical activity (e.g., Decety, Jeannerod, Durozard, & Baverel, 1993). Should we now draw the conclusion that respiration is cognitively penetrable in a manner similar to posture? We believe it is more fruitful to argue that respiration is a physiological process that adapts in a highly flexible manner to changing energetic demands, for example, related to mental activity or exerted effort. How about the converse situation? Suppose we ask subjects to breathe in a predescribed fashion, for example, at a tempo dictated by a metronome. This can only be accomplished by an effortful attempt on the part of the actor to override the natural breathing tendency and adopt another (more difficult) breathing pattern in place. First, the fact that we can voluntarily modulate our breathing pattern does not imply that respiration is cognitively penetrable, for the same reason as forwarded by Fodor (1983) and Pylyshyn (1980, 1999) with regard to vision. Second, it would probably come as no surprise that in such a situation subjects would perform poorly on a secondary cognitive task, because they need attention to monitor and control their respiration. But again, this does not mean that the control of respiration *itself* is attention demanding; it means that when we voluntarily disturb the natural breathing cycle and adopt an "unnatural" pattern instead, we must deploy cognitive resources, the costs of which can be quantified by a dual-tasking paradigm.

SO, IS POSTURE COGNITIVELY PENETRABLE?

Despite the caveats formulated in the preceding, we deem it perfectly reasonable to ask whether posture is cognitively penetrable, especially when we adopt a perspective of motor control as being organized in a hierarchical fashion. Hierarchical models of motor control are quite common (e.g., Rosenbaum, 2010), and figure especially prominently in neurology. Simply put, the top level within the hierarchy is assumed to be responsible for long-range planning processes, and is involved in the selection of movement goals. Furthermore, the top level oversees whether motor performance is successful, and it can initiate a switch to another action plan, if necessary. The top level delegates the implementation of action plans to lower levels, which encode increasingly fine-grained elements of the action, such as sequencing and the regulation of kinematic details. The lowest "online" level is devoted to fast online monitoring and correcting of individual movements. Execution of motor tasks involves the orchestrated activity of each of these levels.

According to Glover (2005), this way of thinking can help to shed light on the question whether movements are cognitively penetrable. Glover (2005) distinguished five levels of motor control, ranging from conscious to automatic control. Importantly, the highest level requires conscious control, and is thus cognitively penetrable. The lowest level, in contrast, involves fast automatic adjustments that take place outside conscious awareness. As a consequence, the lowest level is immune to cognitive influences and is thus cognitively impenetrable. Thus, the higher up in the hierarchy of motor plans we proceed, the more its contents can be modified by cognition, that is, the greater the cognitive penetrability. A similar point was made by Pacherie (2008), who also pointed out that the motor system is characterized by limited cognitive penetrability. Glover (2005) presented evidence of his model, using behavioral evidence (e.g., perturbation studies) and neurological evidence. Although the evidence presented was mainly focused on reach-to-grasp movements, we believe the proposed model can also be applied to the regulation of posture. The top of the hierarchy would then consist of conscious and effortful (attention-demanding) postural adjustments, such as the voluntary decision to initiate a step in a particular direction from quiet stance, attempts to oscillate the body center of mass at a predefined tempo, or situations involving postural challenges, such as walking at a slippery surface. Regulation of posture at the bottom of the hierarchy would likely consist of fast and automatic postural microadjustments that we perform all the time without giving such corrections much thought. In fact, even if we wanted to we could never directly access and control that particular level of motor implementation, as it likely involves spinal feedback loops that are outside our conscious reach.

Now, reduced postural capacities (and the associated increased fall risk) due to aging or pathology can be the result of decrements at any level of the action hierarchy. A reduced ability to control posture at the top level may result, for example, in failing to select an optimal walking route through a cluttered room, or an inability to flexibly adjust posture to changing environmental demands. A reduced ability to control posture at the lowest level might consist in small timing errors (e.g., due to reduced propriocepsis), which in the context of postural equilibrium may make the difference between maintaining balance and experiencing a fall. Note that in the case of deteriorated posture at the online level, the subject may very well be aware that the automatic postural control system has been compromised in some ways, rendering it less reliable. In that case, attention-demanding "support troops" can be brought in to provide extra support for balance, for example, by closely monitoring one's own body, or adopting balance safety strategies. In this respect, attentional resources could be thought of in a similar fashion as cognitively driven activities that aid a degraded visual system.

CONCLUSION

Pylyshyn (1980, 1999) argued that visual processing is cognitively impenetrable. At the same time, cognition can greatly aid the visual system by, for example, active exploration, disambiguation, increasing resolution (such as looking through glasses), etc. In the same way, the control of fast online postural adjustments is cognitively impenetrable, but we can exert some degree of attention-demanding control over it when needed, for example, to compensate for age-related changes in balance safety. Attentional control of posture is especially sensitive to secondary task challenges, as in "talking while walking." Posture-cognition interactions effects are common, across all age groups, but more so in the elderly. This is due in part, we believe, to an age-related change in strategy towards a more conscious control mode of balance. This compensatory mechanism, however, is at risk of cognitive interference, and reduces the ability to perform concurrent postural and cognitive activities. The hierarchical model of cognitive penetrability of actions of Glover (2005) can be used to generate predictions regarding the neural level at which age-related changes in balance take place, and to assess the likelihood of successful cognitive interventions of balance loss.

REFERENCES

Brauer, S. G., Woollacott, M., & Shumway-Cook, A. (2002). The influence of a concurrent cognitive task on the compensatory stepping response to a perturbation in balance-impaired and healthy elders. *Gait and Posture, 15,* 83–93.

Carlson, R. A., Avraamides, M. N., Cary, M., & Strasberg, S. (2007). *Journal of Experimental Psychology: Human Perception and Performance, 33,* 747–756.

Caudron, S., Boy, F., Forestier, N., & Guerraz, M. (2008). Influence of expectation on postural disturbance by proprioceptive stimulation. *Experimental Brain Research, 184,* 53–59.

Damasio, A. D. (1994). *Descartes' error: Emotion, reason and the human brain.* New York: Avon Books.

Decety, J., Jeannerod, M., Durozard, D., & Baverel, G. (1993). Central activation of autonomic effectors during mental simulation of motor actions in man. *Journal of Physiology, 461,* 549–563.

Doumas, M., Smolders, C., & Krampe, R. Th. (2008). Task prioritization in aging: Effects of sensory information in concurrent posture and memory performance. *Experimental Brain Research, 187,* 275–281.

Dunn, B. D., Dalgleish, T., & Lawrence, A. D. (2006). The somatic marker hypothesis: A critical evaluation. *Neuroscience and Biobehavioral Reviews, 30,* 239–271.

Fodor, J. A. (1983). *The modularity of mind: An essay on faculty psychology.* Cambridge, MA: MIT Press/A Bradford Book.

Fraizer, E. V., & Mitra, S. (2008). Methodological and interpretive issues in posture-cognition dual-tasking in upright stance. *Gait & Posture, 27,* 271–279.

Fraser, S. A., Li, K. Z. H., & Penhune, V. B. (2010). Dual-task performance reveals increased involvement of executive control in fine motor sequencing in healthy aging. *Journal of Gerontology B: Psychological Sciences, 65,* 526–535.

Gerrans, P., & Kennett, J. (2006). Introduction: Is cognitive penetrability the mark of the moral? *Philosophical Explorations, 9,* 2–12.

Glover, S. (2005). A hierarchical model of the cognitive penetrability of actions. In A. Raftopoulos (Ed.), *Cognitive penetrability of perception* (pp. 193–208). New York: Nova Science Publishers.

Gomez, P., Zimmermann, P., Guttormsen-Schär, S., & Danuser, B. (2005). Respiratory responses associated with affective processing of film stimuli. *Biological Psychology, 68,* 223–235.

Homma, I., & Masaoka, Y. (2008). Breathing rhythms and emotions. *Experimental Physiology, 93,* 1011–1021.

Huang, H.-J., & Mercer, V. S. (2001). Dual-task methodology: Applications in studies of cognitive and motor performance in adults and children. *Pediatric Physical Therapy, 13,* 133–140.

Huxhold, O., Li, S.-C., Schmiedek, F., & Lindenberger, U. (2006). Dual-tasking postural control: Aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Research Bulletin, 69,* 294–305.

Kotses, H., Westlund, R., & Creer, T. L. (1987). Performing mental arithmetic increases total respiratory resistance in individuals with normal respiration. *Psychophysiology, 24,* 678–682.

Li, K. Z. H., Lindenberger, U., Freund, A. M., & Baltes, P. B. (2001). Walking while memorizing: Age-related differences in compensatory behavior. *Psychological Science, 12,* 230–237.

Li, K. Z. H., Roudaia, E., Lussier, M., Bherer, L., Leroux, A., & McKinley, P. A. (2010). Benefits of cognitive dual-task training on balance performance in healthy older adults. *Journal of Gerontology A: Medical Sciences,* 1344–1352.

McGurk, H., & MacDonald, J. (1976). Hearing lips and seeing voices. *Nature, 264,* 746–748.

Mitra, S. (2003). Postural costs of suprapostural task load. *Human Movement Science, 22,* 253–270.

Mitra, S. (2004). Adaptive utilization of optical variables during postural and suprapostural dual-task performance: Comment on Stoffregen, Smart, Bardy, and Pagulayan (1999). *Journal of Experimental Psychology: Human Perception and Performance, 30,* 28–38.

Pacherie, E. (2008). The phenomenology of action: A conceptual framework. *Cognition, 107,* 179–217.

Paillard, J. (1991). The cognitive penetrability of sensorimotor mechanisms: A key problem in sport research. *International Journal of Sport Psychology, 22,* 244–250.

Prado, J. M., Stoffregen, T. A., & Duarte, M. (2007). Postural sway during dual tasks in young and elderly adults. *Gerontology, 53,* 274–281.

Pylyshyn, Z. (1980). Computation and cognition: Issues in the foundations of cognitive science. *Behavioral and Brain Sciences, 3,* 111–169.

Pylyshyn, Z. (1999). Is vision continuous with cognition? The case for cognitive impenetrability of visual perception. *Behavioral and Brain Sciences, 22,* 341–423.

Redfern, M. S., Jennings, J. R., Mendelson, D., & Nebes, R. D. (2009). Perceptual inhibition is associated with sensory integration in standing postural control among older adults. *Journal of Gerontology: Psychological Sciences, 64B,* 569–576.

Rosenbaum, D. A. (2010). *Human motor control* (2nd Ed.). San Diego: Academic Press/Elsevier.

Scharland, L. C. (2006). Cognitive modularity of emotion. *Canadian Journal of Philosophy, S32,* 213–228.

Schwartz, D. L., & Black, J. B. (1996). Shuttling between depictive models and abstract rules: Induction and fallback. *Cognitive Science: A Multidisciplinary Journal, 20,* 457–497.

Stelmach, G. E., & Worringham, C. J. (1985). Sensorimotor deficits related to postural stability. *Clinics in Geriatric Medicine, 1,* 679–694.

Stins, J. F., Vosse, S., Boomsma, D. I., & de Geus, E. C. J. (2004). On the role of working memory in response interference. *Perceptual and Motor Skills, 99,* 947–958.

Stoffregen, T. A., Hove, P., Bardy, B. G., Riley, M., & Bonnet, C. T. (2007). Postural stabilization of perceptual but not cognitive performance. *Journal of Motor Behavior, 39,* 126–138.

Stoffregen, T. A., Smart, L. J., Bardy, B. G., & Pagulayan, R. J. (1999). Postural stabilization of looking. *Journal of Experimental Psychology: Human Perception & Performance, 25,* 1641–1658.

Teasdale, N., Bard, C., LaRue, J., & Fleury, M. (1993). On the cognitive penetrability of posture control. *Experimental Aging Research, 19,* 1–13.

VanderVelde, T. J., Woollacott, M. H., & Shumway-Cook, A. (2005). Selective utilization of spatial working memory resources during stance posture. *NeuroReport, 16,* 773–777.

Woollacott, M. H., & Shumway-Cook A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait & Posture, 16,* 1–14.